Analysis of floor response spectra in reactor building of NPP with VVER-1500 at air shock wave impact

Dr. V. Korotkov, Mr. D. Poprygin, Mr. K. Ilin, Dr. S. Ryzhov

Atomenergoproekt, TESIS (Moscow, Russia)

Abstract: Nowadays «Atomenergoproekt» institute conducts work for creation of basic design of NPP with VVER-1500. Within this design it is necessary to develop equipment for NPPs that meets requirements of trouble-free operation at special dynamic impacts: seismic activity, air shock wave and aircraft crash. In order to solve such a problem one should know about relevant response spectra. The purpose of this report is to define floor response spectra in reactor building of unitized design with VVER-1500 in equipment installation spots at ASW impact. In the presented report we have applied the licensed finite-element software ABAQUS, version 6.4.4 for determination of dynamic reaction in reactor building. In this case, in accordance with EUR (EUR – European Utility Requirements) a variability of soil properties, characterizing various dynamic properties of soil depending on site location has been estimated. There has been given a justification of a choice of damping in the system. There has been presented a methodical description of estimation of interaction of a structure and foundation when solving a dynamic problem. There has been also presented a description of RB spatial mathematical model and conditions of loading, which were performed in accordance with American standard ASCE.


1. The mathematical model of «structure-foundation» system

In accordance with architectural-civil drawings of NPP with power units VVER-1500 there has been developed the mathematical model of the building reflecting its complicated spatial structure that takes account of various equipment units and soil effect.

Concrete grade B50 was used for reinforced concrete constructions (inner containment) and B30 – for other constructions.

In accordance with EUR [1] at seismic analysis of uniformed power unit it is necessary to use nine sites with various properties given in Table 1.
Table 1. Soils properties

<table>
<thead>
<tr>
<th>Soil site number</th>
<th>Soft soil</th>
<th>Mean soil</th>
<th>Rigid soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Shear wave velocity, m/s</td>
<td>250</td>
<td>350</td>
<td>500</td>
</tr>
<tr>
<td>Soil density, t/m$^3$</td>
<td>2.0</td>
<td>2.2</td>
<td>2.5</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.47</td>
<td>0.40</td>
<td>0.35</td>
</tr>
<tr>
<td>Internal damping</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
</tr>
</tbody>
</table>

The following types of finite elements were used in the mathematical model:

- shell element (S4R) for simulation of walls, floors and shells;
- beam element (B31) for simulation of reactor;
- spring element (SPRING2) for estimation of soil rigid properties;
- dashpot element (DASHPOT2) for estimation of energy diffusion through soil;
- lumped mass element (MASS) for regarding of equipment elements.

Simulation of various equipment units

In accordance with [2] (Section 3.1.7.1) no assessment of interaction of main system (bearing constructions) and subsystem (equipment unit) is required if full mass of the subsystem compose 1% and less of the main bearing construction mass. Table 2 presents a list of equipment its mass and ratio value

$$R_m = \frac{M_{equi}}{M_{bearingconstruction}}$$
Table 2. List of equipment its mass and ratio value

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Mass, MN</th>
<th>Rm, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>15,00</td>
<td>0.5</td>
</tr>
<tr>
<td>Steam generator</td>
<td>7,00</td>
<td>0.3</td>
</tr>
<tr>
<td>ECCS-1</td>
<td>1,50</td>
<td>0.05</td>
</tr>
<tr>
<td>ECCS-2</td>
<td>3,50</td>
<td>0.1</td>
</tr>
<tr>
<td>RCP</td>
<td>1,50</td>
<td>0.05</td>
</tr>
<tr>
<td>Polar crane</td>
<td>6,10</td>
<td>0.2</td>
</tr>
<tr>
<td>Prz</td>
<td>4,00</td>
<td>0.1</td>
</tr>
<tr>
<td>HA-2</td>
<td>3,50</td>
<td>0.1</td>
</tr>
<tr>
<td>PHRS</td>
<td>0,50</td>
<td>0.01</td>
</tr>
<tr>
<td>Quick boron injection system tank</td>
<td>0,60</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Full mass of the reactor building</strong></td>
<td>3071,40</td>
<td></td>
</tr>
</tbody>
</table>

As indicated in Table 2, no one equipment unit exceeds 1%. However, we consider conservatively the reactor model in the form of beam system and the steam generator one – in the form of shell construction as equipment units having got the nearest approximation of ratio Rm to 0.01.

In figures 1 – 4 there are given the reactor building finite-element model fragments corresponding to certain elevations and parts of this structure. Figure 5 gives a general view of the reactor building finite-element model.
Figure 1. Foundation plate of the building at el. – 9.600.

Figure 2. Internal walls and ALA walls at el. +10.800.
Figure 3. General view of the ALA simulator from el. +10.800 to el. +26.600.

Figure 4. General view of the ALA simulator from el. 0.000 to el. +42.000.
Figure 5. General view of the reactor building mathematical model.
2. Determination of soil properties

When considering interaction of a structure with foundation we used formulae [2], obtained from solution of the problem about vibration of stamp on elastic half-space given in figure 6. These formulae are given in Table 3.

![Figure 6. Rectangular stamp.](image)

<table>
<thead>
<tr>
<th>Equivalent spring constant</th>
<th>Equivalent damping coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_x = 2 \cdot (1 + \nu)G \cdot \beta_x \sqrt{BL}$, MH/m</td>
<td>$b_x = \frac{0.576}{V_s} k_x \frac{BL}{\pi}$, MH-c/m</td>
</tr>
<tr>
<td>$k_y = 2 \cdot (1 + \nu)G \cdot \beta_y \sqrt{BL}$, MH/m</td>
<td>$b_y = \frac{0.576}{V_s} k_y \frac{BL}{\pi}$, MH-c/m</td>
</tr>
<tr>
<td>$k_z = 2 \cdot (1 + \nu)G \cdot \beta_z \sqrt{BL}$, MH/m</td>
<td>$b_z = \frac{0.85}{V_s} k_z \frac{BL}{\pi}$, MH-c/m</td>
</tr>
<tr>
<td>$k_{\psi_s} = \frac{G}{1 - \nu} \beta _{\psi_s} \cdot B^2 \cdot L$, MH-m</td>
<td>$b_{\psi_s} = \frac{0.3 \cdot k_{\psi_s} \cdot R_s}{1 + B_{\psi_s} \cdot V_s}$, MH-m-c</td>
</tr>
</tbody>
</table>

Table 3. Lumped representation of structure-foundation interaction at surface of a rectangular base.
\[
\begin{align*}
  k_{\varphi} &= \frac{G}{1-N} \beta_{\varphi} \cdot B \cdot L^2, \text{ MH} \cdot \text{M} \\
  b_{\varphi} &= \frac{0.3 \cdot k_{\varphi} \cdot R_s}{1 + B_{\varphi} \cdot V_s}, \text{ MH} \cdot \text{M} \cdot \text{C} \\
  k_{\varphi} &= \frac{16}{3} \beta_{\varphi} \cdot G \cdot R^3, \text{ MH} \cdot \text{M} \\
  b_{\varphi} &= \frac{1}{1 + B_{\varphi} \cdot \sqrt{k_{\varphi} \cdot I_z}}, \text{ MH} \cdot \text{M} \cdot \text{C}
\end{align*}
\]

In the presented Table:
- \( k_i \) - linear spring;
- \( k_{\varphi} \) - angular spring;
- \( b_i \) - linear damping;
- \( b_{\varphi} \) - angular damping.

\( i = x, y, z \)

Values of empirical coefficients \( \beta_i \) & \( \beta_{\varphi} \) are to be defined per the diagram given in figure 7.

![Figure 7. Diagram for determination of coefficients \( \beta_X, \beta_\Psi, \beta_Z \) depending on relation L/B.](image)

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B – a length of the rectangular foundation side perpendicular to direction of horizontal disturbance, m;
L – a length of the rectangular foundation side parallel to direction of horizontal disturbance, m;

\[ \beta_{\varphi_x} = \beta \Psi, \text{ if } B/L = 1.096 \]

\[ \beta_{\varphi_y} = \beta \Psi, \text{ if } L/B = 0.912 \]

G – dynamic modulus in shearing; \( G = \rho \cdot V_s^2 \)

\( v \) - Poisson’s ratio
\( \rho \) - soil density
\( V_s \) – velocity of spreading of transverse waves

\( I_{xx}, I_{yy}, I_{zz} \) - inertia moments of the structure around axes \( x, y \& z \), respectively passing through the foundation center.

Dimensionless coefficients \( B_{\varphi_x}, B_{\varphi_y}, B_{\varphi_z} \) are defined according to the following formulae:

\[ B_{\varphi_x} = \frac{3(1-v) \cdot I_{xx}}{8 \rho R_x^3}; \]

\[ B_{\varphi_y} = \frac{3(1-v) \cdot I_{yy}}{8 \rho R_y^3}; \]

\[ B_{\varphi_z} = \frac{2 I_{zz}}{\rho R_z^3}; \]

\[ R_x = \frac{4}{3} \frac{B^3 L}{\pi} \] - equivalent radius at rocking around axis \( X \);

\[ R_y = \frac{4}{3} \frac{BL^3}{\pi} \] - equivalent radius at rocking around axis \( Y \);

\[ R_z = \frac{4}{3} \frac{BL(B^2 + L^2)}{6\pi} \] - equivalent radius at torsion in horizontal plane.

Relative damping in soil was defined as follows:
In the above given formulae the values of moments of inertia and complete mass of the building
were defined as a result of calculation by ABAQUS software and have got the following values:

\[ I_{xx} = 4.88 \cdot 10^7 \text{ t} \cdot \text{m} \cdot \text{c}^2 \]
\[ I_{yy} = 4.86 \cdot 10^7 \text{ t} \cdot \text{m} \cdot \text{c}^2 \]
\[ I_{zz} = 2.13 \cdot 10^7 \text{ t} \cdot \text{m} \cdot \text{c}^2 \]
\[ m = 307140 \text{ t} \]

We obtain a value of equivalent radius for foundation plate as

\[ R = \frac{BL}{\pi} = 37 \text{ m} \] and ratio of
deeping value to the equivalent radius corresponds to 12.1:37 \approx 0.3, and in accordance with [2]
we shall neglect the deepening effect.

Equivalent spring constant and damping coefficients in Table 3 are necessary to be distributed
throughout the foundation plate surface. For distributing the integral properties of equivalent
spring and damping we have applied a double symmetry of the foundation plate. Linear values of
springs and damping we shall distribute uniformly (i.e. proportional to weight areas). Therefore

\[ k_{ij} = k_i \frac{\Delta S_j}{S} \]  \hspace{1cm} (3.1)

\[ b_{ij} = b_i \frac{\Delta S_j}{S} \]

here \( i = x, y, z \)
\( \Delta S_j \) - a value of area reduced to j-node, and S – a value of area of the foundation plate.

Linear nodal springs and damping create an integral bending stiffness and damping obtained as follows:

\[
C_{\varphi_x} = \sum_j k_{ij} \cdot r_j^2(y)
\]

\[
C_{\varphi_y} = \sum_j k_{ij} \cdot r_j^2(x)
\]

\[
C_{\varphi_z} = \sum_j k_{ij} \cdot r_j^2(y) + k_{ij} \cdot r_j^2(x)
\]

\[
D_{\varphi_x} = \sum_j b_{ij} \cdot r_j^2(y)
\]

\[
D_{\varphi_y} = \sum_j b_{ij} \cdot r_j^2(x)
\]

\[
D_{\varphi_z} = \sum_j (b_{ij} \cdot r_j^2(y) + b_{ij} \cdot r_j^2(x))
\]

In formulae (3.2) \( r_j (x) \) and \( r_j (y) \) - are components of j-point radius-vector coming out of the geometrical center.

However, the integral bending rigidity and damping obtained by formulae (3.2) are considerably less than values of equivalent spring constant and damping presented in Table 3, therefore, for full compliance with the theory of stamp, it is necessary to compensate this difference as follows (by analogy with [3]):

\[
\Delta c_{\varphi_x} = k \varphi_x - c_{\varphi_x} ; \quad \Delta B_{\varphi_x} = B_{\varphi_x} - D\varphi_x
\]

\[
\Delta c_{\varphi_y} = k \varphi_y - c_{\varphi_y} ; \quad \Delta B_{\varphi_y} = B_{\varphi_y} - D\varphi_y
\]

\[
\Delta c_{\varphi_z} = k \varphi_z - c_{\varphi_z} ; \quad \Delta B_{\varphi_z} = B_{\varphi_z} - D\varphi_z
\]

We distribute values of compensative rigidity and damping (3.3) over the foundation plate surface by analogy with (3.1) proportionally to weight areas.

According to the described method there has been developed an off-line software permissive to define relevant rigidity and damping in every node of foundation plate for nine declared sites. This software took into account that since values of the linear damping always had got very high values
(up to 66% at vertical direction), therefore, in compliance with [4], they were limited to 15% of critical values.

Tables 4, 5, 6 present results of calculations according to presented methods for soils corresponding to sites 1, 5 & 9, that are of interest for ASW.

For obtaining loads from ASW there has been applied off-line software WOLNA, intended for defining ASW parameters, when waves interact with an obstacle of complex shape, and developed in accordance with [5]. In the result of ASW calculation there were defined dependences of pressure upon time, which then were used as initial loads for dynamic analysis according to software ABAQUS.

Methods of dynamic analysis

The dynamic analysis was performed using direct integration of equation of motion in time:

\[
K\{U\} + C\{\dot{U}\} + M\{\ddot{U}\} = P(t)
\]

where 
\(K\) - stiffness matrix, 
\(M\) – mass matrix, 
\(C\) – damping matrix, 
\(P(t)\)- vector of initial dynamic load characterizing ASW

For consideration of damping properties in RB design there was used Rayleigh damping 

\(C_1 = \alpha M + \beta K\),

that allows for defining apparently the matrix of constructional damping.

In addition to Rayleigh damping the system has considered damping in soil \(C_2\) characterizing energy outflow into soil, therefore, in the initial equation

\(C = C_1 + C_2\)

It is necessary to note that soil contains hysteresis damping of level 0.03 – 0.05 depending on a site involved that characterizes friction in material. Consideration of this damping is covered conservatively by Rayleigh formula.

Integration step in time was selected in accordance with [2] so that reduction of this step twice resulted in change of dynamic reaction not more than by 10%. In this concern the integration step in time was adopted as 0.002 s.
3. Results of the analysis

As a result of the dynamic analysis there were obtained floor accelerograms occurring at ASW impact. Then relevant response spectra were built up, and then there was carried out enveloping of the spectra as per interesting nodes of elevation for two directions of ASW impact – for X and for Y. The spectra correspond to two values of damping – 2% & 5%.

The spectra were built up for frequency range 0 – 150 Hz with indication of ZPA value, i.e. maximum value of acceleration in place of the spectrum construction. The involved frequency range was divided in to two parts, in the first of which (0 – 60 Hz) the spectra were calculated with increment of frequency 0.1 Hz, and in the second one (60 – 150 Hz) increment of frequency amounted to 0.4 Hz. Such small increments per frequency were selected in accordance with [2], in order to observe peak values of spectral accelerations. The response spectra take into consideration the dispersion of inputs by way of 15% extension in the frequency range.

Final response spectra are given in Appendix A, where only 3 spectra are presented with maximum values of accelerations.

Table 4. Site №1, Vs = 250 m/s, ρ = 2 t/m³; ν = 0,47.

<table>
<thead>
<tr>
<th>Equivalent spring constant</th>
<th>Equivalent damping coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_x = 2,619 \cdot 10^4$, MH/m</td>
<td>$b_x = 0,859 \cdot 10^3$, MH/m·s (15%)</td>
</tr>
<tr>
<td>$k_y = k_x$</td>
<td>$b_y = b_x$</td>
</tr>
<tr>
<td>$k_z = 3,455 \cdot 10^5$, MH/m</td>
<td>$b_z = 0,986 \cdot 10^3$, MH/m·s (15%)</td>
</tr>
<tr>
<td>$k_{\phi_x} = 3,509 \cdot 10^7$, MH·m</td>
<td>$b_{\phi_x} = 1,012 \cdot 10^6$, MH·m·s (12%)</td>
</tr>
<tr>
<td>$k_{\phi_y} = 3,458 \cdot 10^7$, MH·m</td>
<td>$b_{\phi_y} = 0,87 \cdot 10^6$, MH·m·s (10%)</td>
</tr>
<tr>
<td>$k_{\phi_z} = 3,535 \cdot 10^7$, MH·m</td>
<td>$b_{\phi_z} = 0,707 \cdot 10^6$, MH·m·s (13%)</td>
</tr>
</tbody>
</table>

Table 5. Site №5, Vs = 800 m/s, ρ = 2,2 t/m³; ν = 0,4.

<table>
<thead>
<tr>
<th>Equivalent spring constant</th>
<th>Equivalent damping coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_x = 2,809 \cdot 10^5$, MH/m</td>
<td>$b_x = 2,813 \cdot 10^3$, MH/m·s</td>
</tr>
<tr>
<td>$k_y = k_x$</td>
<td>$b_y = b_x$</td>
</tr>
<tr>
<td>$k_z = 3,438 \cdot 10^5$, MH/m</td>
<td>$b_z = 3,112 \cdot 10^3$, MH/m·s</td>
</tr>
<tr>
<td>$k_{\phi_x} = 3,492 \cdot 10^8$, MH·m</td>
<td>$b_{\phi_x} = 3,113 \cdot 10^6$, MH·m·s</td>
</tr>
<tr>
<td>$k_{\phi_y} = 3,440 \cdot 10^8$, MH·m</td>
<td>$b_{\phi_y} = 2,674 \cdot 10^6$, MH·m·s</td>
</tr>
<tr>
<td>$k_{\phi_z} = 3,982 \cdot 10^8$, MH·m</td>
<td>$b_{\phi_z} = 2,544 \cdot 10^6$, MH·m·s</td>
</tr>
</tbody>
</table>
4. Conclusion

The presented report deals with response spectra on elevations of installation of equipment in unified NPP with VVER-1500 at air shock wave impact.

The problem was being solved in three-dimensional model based on finite-element program ABAQUS-6.4.4. They have taken into consideration variability of soil properties, damping in system «structure-foundation», as well as some other requirements satisfying American standard ASCE.

In future, based on the developed unified mathematic model there will be defined response spectra at aircraft crash and at seismic impact.

5. Reference

1. AES92/EUR - CAR2 - chapter 4.2 – R – 1
4. Standard Review Plan 3.7.2 Seismic System Analysis, NUREG-08000 Rev.1, August 1989
5. RD95_10528-96 Minatom of Russia. Manual for definition of parameters of shock waves at external explosions and loads on civil constructions of NPPs.
Response spectra along X-axis at elevation +10.800 (surrounding constructions) at ASW impact

ZPA = 17.4 m/s²

Response spectra along Y-axis at elevation +10.800 (surrounding constructions) at ASW impact

ZPA = 14.5 m/s²
Response spectra along Z-axis at elevation +10.800 (surrounding constructions) at ASW impact

ZPA = 7.2 m/s²

Response spectra along X-axis at elevation +4.200 (area of polar crane supports) at ASW impact

ZPA = 3.894 m/s²
Response spectra along Y-axis at elevation +42.000 (area of polar crane support) at ASW impact

\[ \text{ZPA} = 4.5408 \text{ m/s}^2 \]

Response spectra along Z-axis at elevation +42.000 (area of polar crane support) at ASW impact

\[ \text{ZPA} = 1.908 \text{ m/s}^2 \]
Response spectra along X-axis, upper supports of steam generator (containment area) at ASW impact

ZPA = 1.7 m/s²

Response spectra along Y-axis, upper supports of steam generator (containment area) at ASW impact

ZPA = 4.4 m/s²

Frequency, Hz

Acceleration m/s²

with extension 0.15 and damping 0.02
with extension 0.15 and damping 0.05
6. References

1. ABAQUS Theoretical manual, version 6.4.